Experimental Investigation on Cracked Body with Adhesive-Bonded Reinforcement

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ABSTRACT

A new method to reinforce a cracked body with adhesive bonding is presented in this paper. The advantages of this method were verified by failure load measurement, stress measurement by strain gauges and fatigue test of both plates and vessels. Adhesive layer was able to transfer load efficiently, which enabled reinforcing patch to share the load, it resulted in improvement on stress concentration near crack tip and increase in load-bearing ability of a cracked body, which can meet the requirement of engineering practice to its fatigue life.

INDRODUCTION

CVDA (Defect Assessment Code of Pressure Vessels (China)) is one of powerful mechanics methods to assess the fatigue life of a vessel with defects, by virtue of which if a crack surpasses a critical crack in size under certain conditions, which is called over-critical defect, the vessel is discarded as useless. For economic reasons it is put forward from engineering practice that whether there is a method to delay crack growth so that a vessel with over-critieal cracks can continue to use or its working life can be prolonged. An expedient measure usually adopted in some factories is that the crack tip is ground off with abrasive wheel and weld material is heaped up there. But there is inevitably residual stress caused by welding, which in some situation will make the initial crack propagating more quickly or will creat more small cracks around it. The purpose of the present paper is to develop a adhesive-bonded reinforcement technique, which is called ABR, as a method to repair and patch cracked body, to try to solve the above problem. It is expected that the technique will be applicable to not only the reinforcement of pressure vessels and piping but also the reinforcement and consolidation of steel bridges and the reparation of crack in airplane fuselages.

The basic principles of ABR method are that it enables a reinforcing patch to adhere to a cracked body to form a firm composite solidity, so that the load applied to the cracked body will partly be transfered to the reinforcing patch and stress concentration near crack tip will be decreased. From this viewpoint, ABR method is especially useful for the cracked body which is subjected to fatigue load. Although there are some work reported in literature, ABR method is still in its early stage of development. In this paper the advantages and effectiveness of ABR method were demonstrated by experiment which consists of failure load measurement, stress measurement by strain gauges and fatigue test with both plates and vessels.

SPECIMEN PREPARATION

Specimens are divided into two types, test plates and test vessels, which are all made of 16 MnR steel. Its mechanical properties are listed in Table 1, where σ_y is yield stress, σ_b ultimate stress, σ_a allowable stress, E elastic modulus and δ ductility.

Table 1 Mechanical properties of 16MnR steel

σ_y (MPa)	σ_b (MPa)	σ_a (MPa)	E (MPa)	δ (%)
350	520	175	210,000	21

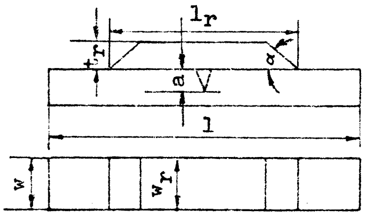

Fig. 1(a) ABR test Plate with surface crack

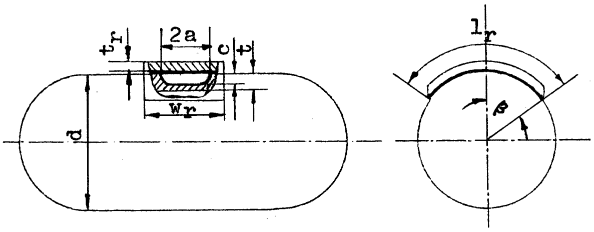

Fig. 1(b) ABR test vessel with crack

ABR test plate with surface crack, shown in Fig. 1(a) was designed for simplicity and ease in experimental observation. The geometry of ABR test vessel with crack is shown in Fig. 1(b), in which if c=t, it means the crack is a through crack. The crack in plates was made by electrosparking wire saw with a molybdenum wire of diameter 0.10 mm. Surface crack in test vessels was made by milling with a milling cutter of thickness 0.20 mm. The vessels with through crack were the waste vessels, which had been discarded after investigation of crack fatigue propagation in pressure vessels.

The adhesive adopted is a single component modified epoxide adhesive with its shear strength property at room temperature equal 33.4 MPa. The adhesive layer thickness of ABR test plate was controlled about 0.15 mm by a simple clamp device made of bolts, nuts and steel plates. The ABR test plates were cured in an oven at the temperature 140°C for 3 hours. The adhesive layer thickness of ABR test vessel was not strictly controlled, amounting to about 0.1 mm to 0.5 mm, and in some small zone of bonded surface, it was allowed not to exceed 1 mm in view of difficulties in holding the uniform adhesive layer of about 0.15 mm on curved surface of practical vessels. The ABR test vessel was kept at the temperature between 150°C and 130°C for 3 to 4 hours with infrared ray heaters. The adhesive bonding technique is considered to be completed with the following procedure: removing rust - abrading with emery paper - degreasing with acetone - sandblasting with corundum or carborundum - applying adhesive - putting reinforcing patch to cracked body - fixing with clamp device - curing at elevated temperature.

STATIC TEST AND DISCUSSION

1. Static test for ABR test plates

Failure stress measurement for ABR test plates with surface crack was carried out on a hydraulic test machine. In this investigation, the failure stress is defined as the stress the test plates or vessels undergo, when fracture failure takes place at the initial crack or debonding, which phenomena is defined as the initiation or growth of crack in adhesive layer or in the interface of adhesive layer and metal, near the edge of reinforcing patch. The geometrical dimension of the test plates is listed in Table 2, where nomenclatures of l, w, t, l_r, w_r, t_r, and α are shown in Fig. 1(a).

Table 2 Geometrical dimension of ABR plates

Type	l (mm)	w (mm)	t (mm)	l_r(mm)	w_r(mm)	t_r(mm)	α (deg.)
A	340	20	10	160	20	7	18
B	280	30	7.4	120	30	4	90

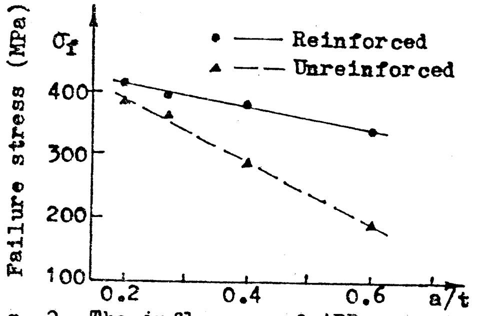

Fig. 2 The influence of ABR on failure stress of cracked plates (a - crack depth, t - cracked plate thickness).

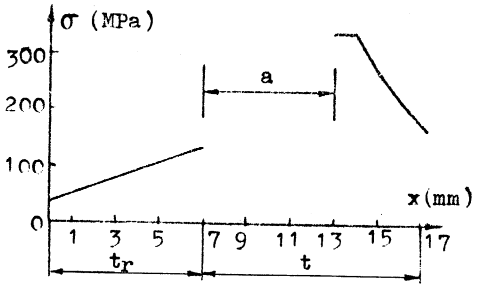

Fig. 3 Stress distribution aling crack stretch for ABR plate with surface crack (load equal 4 ton).

It is indicated by the results of failure stress measurements for both reinforced and unreinforced test plates (see Fig. 2) that there is a greater increase in failure stress σ_f for deep crack than for shallow crack. It has been observed from the measurements that for deep crack, e.g. a/t = 0.6, fracture failure first occurred at the initial crack in metal and it caused consequential shear failure of adhesive layer; for shallow crack, e.g. a/t=0.2, debonding first appeared at the edge of reinforcing patch and further growth of debonding caused consequential fracture at the initial crack in metal. The results in Fig. 2 is able to be standed for by the above mentioned phenomenon. For ABR test plates with deep crack, comparatively much load is transfered through adhesive layer to reinforcing patch, as a result, failure stress is greatly increased. For ABR test plates with shallow crack, after the undergone stress arrives near the yield stress of 16 MnR steel, the adhesive layer, which has low ductility, is not able to follow the plate to continue deforming, which has high ductility and high fracture stress, therefore there is a less increase in failure stress.

Stress distribution in ABR plate was measured by strain gauges with the instrument of Super data log 7V08, produced by Japan NEC SAN-EI instrument Ltd.. Fig. 3 shows the result of stress measurements of an ABR test plate with a crack a = 6 mm, the dimension of which is of type A in Table 2. Most part of the ligament is still in elastic scope, even under the load of four ton which is the fracture failure load of the unreinforced cracked plate with same dimension. It is estimated from the area under the stress distribution curve that one third of the total load is undertaken by the reinforcing patch.

2. Static test for ABR test vessels *

Table 3 hydraulic test results of ABR vessels with crack

test vessel	l (mm)	d (mm)	t (mm)	2a (mm)	l_r (mm)	w_r (mm)	t_r (mm)	P_d (MPa)	P_y (MPa)	P_f (MPa)
V1	1200	250	5	80	240	240	5	7	14	12.6
V2	1200	250	5	80	240	240	5	7	14	15

Hydraulic test for ABR vessels with a through crack was performed on a hand-driven pressure pump to inspect the load-bearing ability of the vessels. Its results are listed in Table 3, where nomenclatures l, d, t, l_r, w_r, t_r and

2a are shown in Fig. 1(b), P_d, P_y and P_f are design, yielding and failure pressure of the vessels respectively. Test vessel V1 was able to bear 0.9 times of yielding pressure, although it was found that there were some defects in adhesive layer appearing during the bonding procedure. The failure pressure of vessel V2 was as high as 1.07 times of P_y by strict controlling of adhesive bonding procedure. The failure type of the test vessels was leakage caused by debonding. When the pressure the vessels undertook arrived near or exceeded P_y, debonding appeared both at the edge of reinforcing patch and near crack. As the debonding zone developed further, hydraulic liquid leaked out through the debonding zone.

Table 4 The dimension of the test vessel for stress measurement

Test vessel	l (mm)	d (mm)	t (mm)	2a (mm)	c (mm)	w_r (mm)	t_r (mm)	β (deg.)	P_d (MPa)	P_y (MPa)
V3	1200	250	4.5	60	3.5	240	5	55	6.3	12.6

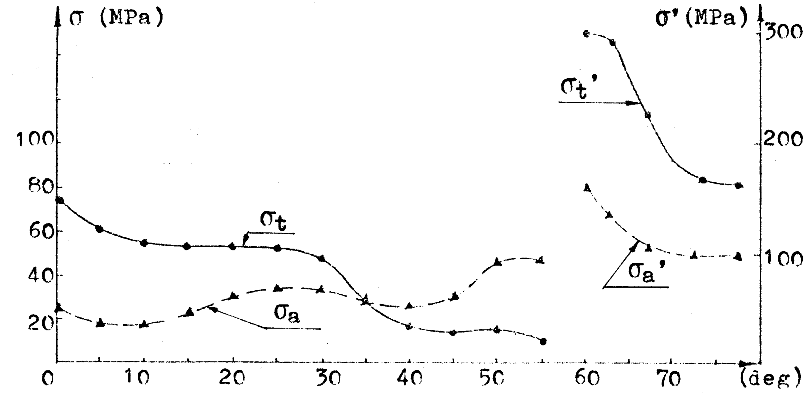

Fig. 4 Stress distribution on test vessel V3 (σ_t, σ_a - tangential and axial stress on reinforcing patch, σ_t', σ_a' - tangential and axial stress on vessel wall respectively).

The test vessel used to measure stress distribution was an ABR test vessel with a surface crack, the geometrical dimension of which is listed in Table 4, where its dimensional notation is shown in Fig. 1(b). Strain gauges were located on the reinforcing patch and outer wall of the vessel, for it was difficult to adhere strain gauges on to the inner wall of the vessel. The result of stress measurement is shown in Fig. 4. It is exhibited from the stress distribution curve in Fig. 4 that the tangential stress at the reinforcing patch is comparatively low near its edge and comparatively high toward its centre and becomes highest just above the crack. As a comparison, the highest stress in the reinforcing patch, i.e. 77.1 MPa, is about 40% of the tangential stress, i.e. 194 MPa, without the influence of ABR and crack.

It is proved from the above tests both for plates and vessels that load is able to be transfered through adhesive layer to reinforcing patch effectively and the load-bearing capacity of a cracked body is increased, therefore the stress concentration near crack is improved.

FATIGUE TEST AND DISCUSSION

1. The fatigue test of ABR test plates

Fatigue test of ABR test plates was performed on a program-controlled high-frequency fatigue test machine, with frequency of about 180 Hz, and two sets of magnifying glass of about 30 times magnification were employed to observe the appearance and propagation of crack in metal. The ABR test plate with a surface crack shown in Fig. 1 (a) which served as fatigue specimen is capable of meeting the need that the fatigue behaviors of both the initial crack in metal and the adhesive layer are detected. If failure occurs at the initial crack in metal, not at the adhesive layer, when the plates are subjected to pulsating load with maximum cyclic stress equal to the allowable stress σ_a, ABR technique is proved to be succesful. The fatigue experimental results of reinforced and unreinforced plates with crack are shown in Fig. 5. It is turned out from the two curves in Fig. 5 that the fatigue life of reinforced cracked plates is about 100 times as high as that of unreinforced cracked plates, if the load applied to them are equal. It should be pointed out that in this study the initial crack is not sharp enough which is actually a notch with radius of about 0.1 mm, and the fatigue life in Fig. 5 is defined as crack initiating life when a small crack with its depth equal about 0.2 mm is found by the magnifying glass. The arrangement of the tests with such a notch is based on the consideration that when ABR method is applied to engineering practice, it is better to remove the sharpness of crack tip by means of an abrasive wheel or to drill a small hole at crack tip for simplicity and present experimental results are employed with proper computation to assess the safety and fatigue life of engineering ABR structure.

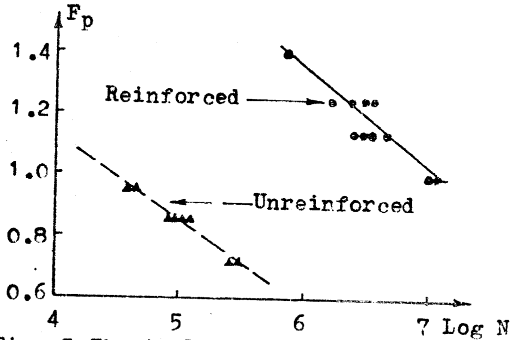

Fig. 5 The influence of ABR on fatigue life of cracked plates for a/t= 0.2 (F_p - σ_{max}/σ_a).

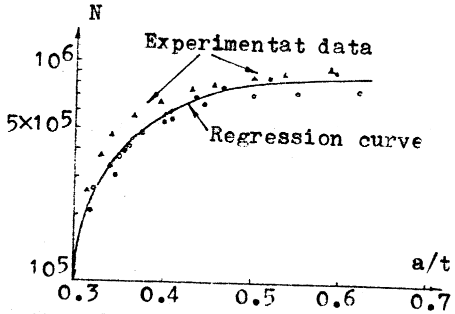

Fig. 6 Fatigue crack growth of ABR test plates.

It was observed from fatigue test of ABR test plates that there were two main types of failure, one being the fatigue crack initiation and its propagation in metal, corresponding to low loads which are not greater than 1.25 times of allowable stress σ_a, and the other debonding near the edge of reinforcing patch, corresponding to higher loads which exceed 1.39 times of σ_a. When debonding appeared, the debonding zone continued growing under cyclic loading, till it arrived near the initial crack in metal, which caused the immediate fracture of cracked plates because of complete loss of reinforcing function. Therefore the fatigue life curve of ABR test plates can be looked upon as the conservative life curve of the adhesive layer. Under pulsating load with maximum cyclic stress σ_{max} equal to σ_a, the adhesive layer of ABR plates is able to undergo 10 million times of stress cycles, from which ABR method is proved to meet the requirement of its application to engineering practice.

Fig. 6 shows the experimental result of fatigue crack propagation of ABR test plates under pulsating load with $\sigma_{max}=\sigma_a$, the propagation life till fracture is as high as about 0.7 million cycles. As a comparison, the fatigue life of unreinforced cracked plates under same test conditions is assessed about 7,100 cycles. Consequently, it is considered that ABR method is able to delay crack propagation about 100 times.

2. The fatigue test of ABR test vessels

The fatigue test for ABR test vessels was performed on a home-made low frequency fatigue test machine, which was specially designed for fatigue test of pressure vessels. The test vessels were subjected to cyclic internal pressures of frequency 12-18 cycles per minute. The experimental results of the test vessels are shown in Table 5, where c/t is the ratio of crack depth to vessel wall thickness, P_{max}/P_d the ratio of maximum cyclic pressure to design pressure, P_{min}/P_d the minimum cyclic pressure to design pressure. The failure pressure of vessel V5 with a through crack still reached yielding pressure, after undergoing 17,800 cycles, which means that the patched crack and the adhesive layer is not completely damaged. Test vessels V7 and V8, in which two cracks with similar size were prefabricated, had comparatively high fatigue life and fatigue failure occurred not at the patched crack but at the welding zone between cynlinder and nozzle, a small through crack appearing in the zone and hydraulic liquid leaking out ftom it.

Table 5 The experimental results of the ABR test vessels

Test vessel	2a (mm)	c/t	P_{max}/P_d	P_{min}/P_d	N_f (cycles)
V5	80	1	1	0	17,850
V7	60	3.5/4.5	1.03	0	34,050
V7	60	3.5/4.5	1.03	0	34,050
V8	60	3.5/4.5	1.03	0	48,950
V8	60	3.5/4.5	1.03	0	48,950

Actually the real fatigue life data of ABR test vessels were not obtained, but it is indicated from the above test that the ability of cracked vessels to resist fatigue is greatly raised by ABR method, despite that the test vessels are all considered to contain over-critical cracks according to CVDA.

CONCLUSIONS

1. The reinforcing patch is able to share the load which is transfered from cracked body through the adhesive layer to it, thus the stress concentration near crack is improved and the load-bearing ability of cracked body is increased. 2. ABR method is valid for increasing the fatigue resistance of cracked body. The fatigue life of the test plates with surface crack a/t=0.2 is prolonged about 100 times by ABR method; the ABR test vessels with over-critical cracks is able to undergo more than 30,000 times of pressure cycles under pulsating pressure with maximum pressure equal to design pressure. 3. The adhesive layer has a good ability of transferring load and satisfied fatigue resistance. Under conditions that the stress applied to ABR specimen is near the yielding stress, no debonding takes place and the adhesive layer is able to bear 10^7 times of stress cycles with maximum cyclic stress equal to allowable stress under pulsating load. 4. The ABR method presented in this paper is feasible, it is suggusted that this method be applied to engineering practice.

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